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Fabrication of an optical lens array using ultraviolet light and ultrasonication

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ABSTRACT

A technique to form an optical lens array using an ultraviolet (UV)-curable resin and ultrasound was investigated. A UV-curable gel film was formed on a glass plate having four lead zirconate titanate (PZT) transducers. Excitation of the transducers generated a lattice flexural vibration mode on the glass plate. The acoustic radiation force acted to deform the surface of the gel film, so that a lens array could be fabricated on the gel film. The lens array was exposed to UV light under ultrasonication to cure the UV-curable film. The quality factor of the transducer resonance was decreased upon curing of the resin film because the cured resin dampened the vibration of the plate. The acoustic characteristics of the UV-curable gel film were measured by using an ultrasound pulse technique at the MHz range. The sound speed of the gel increased from 987 to 1006 m/s (increase of 1.9%) as the UV exposure time increased. The attenuation coefficient also increased and the larger attenuation of the resin caused the lens array to have a lower quality factor.

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1. Introduction

Optical lens arrays are powerful tools that can control the distribution of light intensity and play an important role in the optical industrial field for applications such as liquid crystal displays, optical communication devices, and optical sensors for wavefront aberrations. A lens array can be fabricated using various methods, such as by primitive metallic molding with etching processes [1]. The ion diffusion method can be used to fabricate a microlens array by changing the refractive index of the glass substrate gradually by exposure of the substrate to ions [2–4]. The refractive index of the glass substrate depends on the density of the ion, and the graded distribution of the refractive index in the glass can be obtained by exchanging the ions in the glass substrate with other ions. Several methods for the fabrication of optical microlens arrays have been developed to downsize these optical components. In the reflow method [5], a lens array can be fabricated by melting a resist film on a substrate and utilizing the surface tension of the resist. However, these microlens array fabrication techniques require costly equipment and multiple fabrication steps.

Nakagawa and colleagues have proposed a technique for the fabrication of periodic structures for optical device applications using acoustic waves [6,7]. An optical phase grating can be fabricated in a Ta_2O_5 thin film by generating a standing-wave field of surface acoustic waves (SAW) on a substrate during sputtering of the film. There have been several reports in the literature on techniques for the handling of liquids using the acoustic radiation force of sound waves. Kondoh and colleagues have reported the transport of droplets using SAW on a lithium niobate substrate and the acoustic radiation force [8,9]. Friend et al. have also reported microfluidic flow induced by SAW [10,11]. Ding et al. have reported a noncontact ultrasound transportation technique for liquid that utilizes a high-intensity acoustic field [12]. Wallrabe's group has performed several studies on variable-focus liquid lenses that employ hydrogels [13,14]. The application of such techniques has enabled the shape and focal length of a variable-focus lens to be changed by the radiation force of sound waves [15]. Our group has investigated an optical lens with a variable focal length using ultrasound vibration [16–18], and a lens array with a variable focal length and lens pitch was successfully developed [19]. Here, we propose a simple technique for the formation of a lens array using an ultraviolet (UV)-curable resin and ultrasound.

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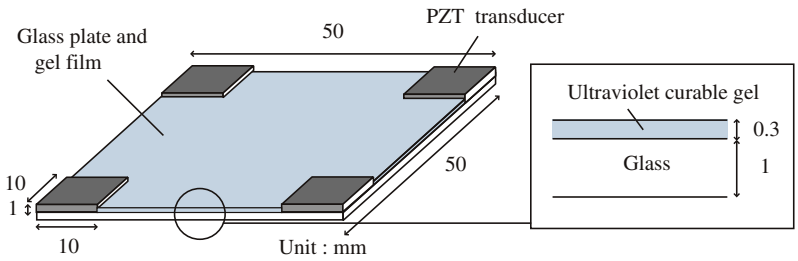

Fig. 1. Configuration of the gel film, glass plate, and four transducers.

The lens profile was controlled by an acoustic radiation force and the curing state of the resin was monitored through the electric characteristics of the ultrasound transducer. The acoustic characteristics of the resin under UV exposure were also investigated.

2. Materials and methods

In the fabrication process of the lens array, a 300 μm thick gel film of UV-curable resin (X-34-4184(A/B), Shin-Etsu Chemical, Tokyo, Japan; refractive index: 1.40; specific gravity: 1.03; viscosity after mixing: 2.7 Pa s; coefficient of linear contraction: 0.1%) was formed on a square glass plate ($50 \times 50 \times 1\ mm^3$) in a darkroom, as shown in Fig. 1. Four rectangular piezoelectric lead zirconate titanate (PZT) transducers ($10 \times 10 \times 1\ mm^3$) were bonded at the four corners of the glass plate using epoxy resin. The resin can be cured by mixing the X-34-4184-A and -B gels (the ratio of A:B was 1:1 in the prototype) and irradiation with UV light with a total energy of 2000 mJ/cm^2 and a wavelength of 365 nm. Under UV light exposure, a platinum catalyst is activated so that the resin can be cured through a hydroxylation reaction. The curing time is dependent on the temperature, where a higher temperature gives a shorter curing time; the curing times at 25, 50, and 100 °C after exposure to UV light at 2000 mJ/cm^2 were approximately 60 min, 5 min, and 30 s, respectively. Electrical excitation of the PZT transducers at the resonance frequency of the glass plate generates a lattice flexural vibration mode on the plate, and different acoustic energy densities are produced in the gel and air at the gel surface. The acoustic energy difference induces a static force, known as the acoustic radiation force [20,21], in the gel that causes its surface to be statically deformed toward the air. The gel can be cured during deformation under ultrasonication by irradiation with UV light.

3. Fabrication of the lens array

Fig. 2 shows the representative vibration mode for the glass plate at 91 kHz, which was predicted by finite element analysis (FEA) using the commercial FEA software ANSYS 11.0 (ANSYS Inc., Canonsburg, PA, USA). The fundamental flexural vibration mode of the transducers generates a lattice vibration mode in the glass plate. Fig. 3 shows the surface profile for the gel film on the glass plate excited with an input voltage of 25 V_{pp} at around 90 kHz that was measured using a confocal laser microscope (LT-9000, Keyence, Osaka, Japan). The measurement area was $40 \times 40\ mm^2$ at the center of the plate. The gel deformation pattern corresponds to the flexural vibration mode for the glass plate because the acoustic radiation force generated at the loop points was larger, and a lattice lens array was fabricated on the gel film. The number of lenses among the four transducers was 21. The lens pitch was approximately 6.8 mm, which corresponds to half the wavelength of the flexural vibration of the plate. The lens array at the gel surface was exposed to UV light with a wavelength of 365 nm and at 0.085 mW/cm^2 during ultrasonication, so that the

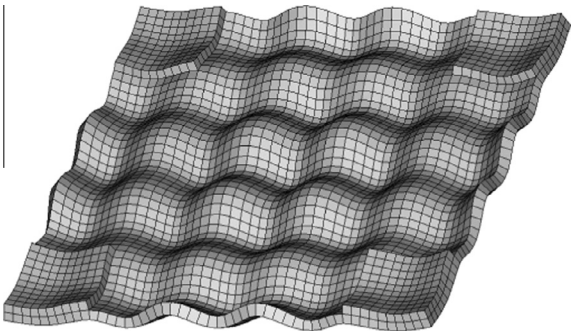

Fig. 2. Vibration mode for the glass plate at 91 kHz as calculated by FEA.

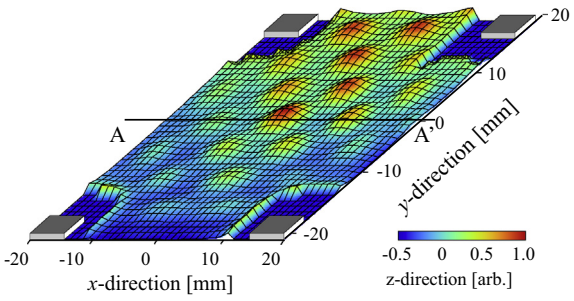

Fig. 3. Surface profile for the UV-curable gel at 90 kHz.

UV-curable film was cured and the deformation was maintained. The surface temperature of the gel was measured with a radiation thermometer and was slightly above room temperature (20 °C) to 30 °C due to attenuation of the high-intensity ultrasound.

Fig. 4 shows cross-sectional profiles for the gel film scanned along the line A–A′ in Fig. 3 at several UV exposure times during ultrasonication. The profiles were scanned 20 s after switching off the ultrasound and UV light, and one scan was completed in 2 s. Thus, the gel was under continuous UV light irradiation and ultrasonication, except during the cross-sectional profile measurements and during measurements of the frequency characteristics of the electrical admittance. When the ultrasonication was switched off, the acoustic radiation force did not act on the surface of the gel, so that the gel returned to the default profile through a transient state. Fig. 5 shows the temporal change in the height of the lens at the center of the glass plate ($(x,y) = (0,0)$). These results indicate that the transient response time of gel motion increased significantly after ca. 10 min upon curing of the gel, and the gel could not return to the default profile within 20 s. There was a large variation in the lens height of the lens array because the lens height correlates with the vibration amplitude of the glass plate. The larger electric input gives a larger lens height due to the resulting larger acoustic radiation force, and the lens height is gradually

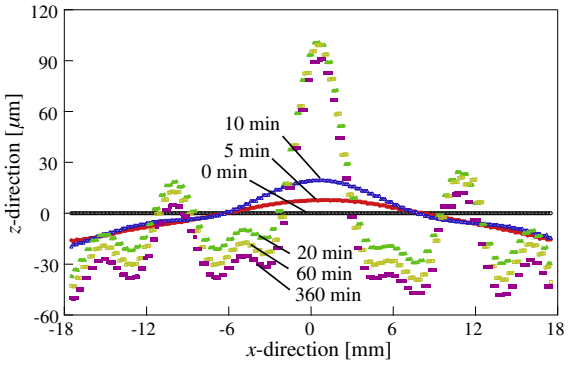

Fig. 4. Cross-sectional profiles for the gel along line A–A′ in Fig. 3 for several UV exposure and ultrasonication times.

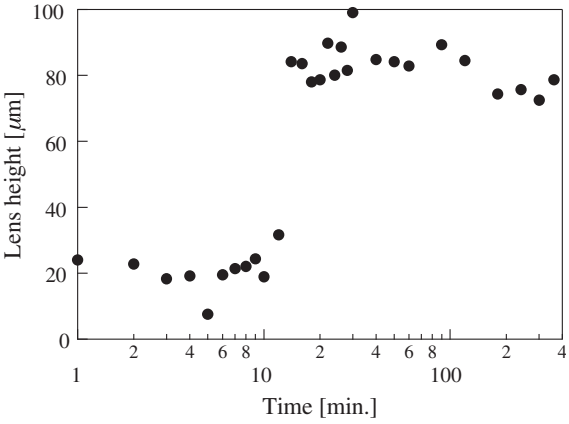

Fig. 5. Temporal change in lens height at the center of the glass plate.

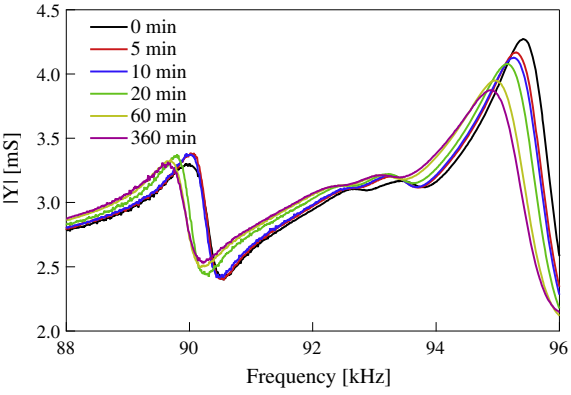

Fig. 6. Temporal change in the frequency characteristics of the electrical admittance for the lens array.

decreased with increasing distance from the center of the glass plate. The asymmetric profile of the lens array is attributed to the contact condition and the individual differences in the PZT transducers. The height of the lens at the center of the plate and the average lens height of the four lenses that surround the central lens were 91 and 34 μm, respectively. The distribution of light transmitted through the lens array was calculated by ray tracing, and the focal lengths of the three lenses at the center along the line A–A′ in Fig. 4 after 360 min were estimated to be 205, 56, and 126 mm from left to right.

Fig. 6 shows the frequency characteristics of the electrical admittance measured for the lens array. There were several resonance

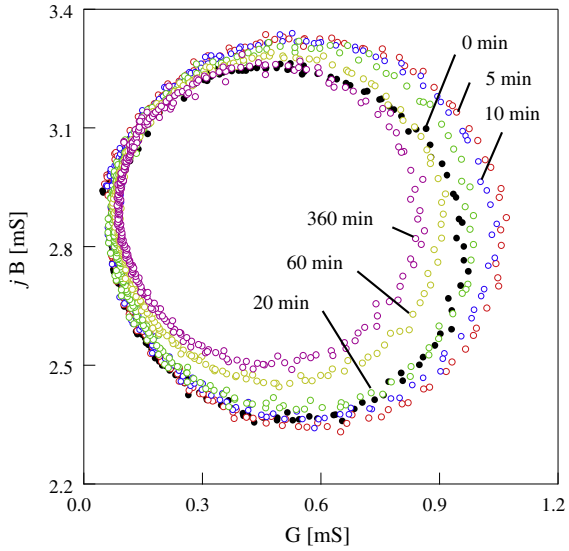

Fig. 7. Change in the admittance loop at 90 kHz with respect to the UV exposure and ultrasonication times calculated from Fig. 6.

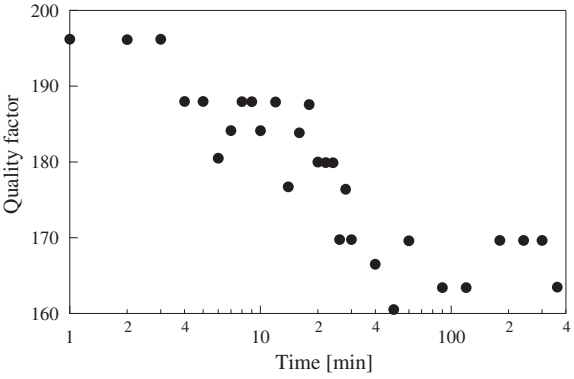

Fig. 8. Change in quality factor at 90 kHz with respect to the UV exposure and ultrasonication times calculated from Fig. 7.

frequencies of the lattice vibration mode between 20 and 200 kHz, which decreased with curing time. The gradual formation of the lens array with time, as shown in Fig. 4, indicates that the gel moved to the loop positions of the lattice flexural vibration mode for the glass plate due to the acoustic radiation force from the flexural vibration. This result implies that the gel film at the loop positions acts as an additional mass. Fig. 7 shows the change in the admittance loops on the complex plane with respect to time around the resonance frequency of 90 kHz in Fig. 6. The change in the quality factor calculated from the admittance loops is shown in Fig. 8. The quality factor decreased gradually under UV light exposure; if we assume that the experimental result of the change in the quality factor can be fitted with an exponential function, the value of the quality factor converges to approximately 166 and a resin curing time constant is 21.4 min. These results indicate that the resistance increased and the quality factor decreased upon curing of the resin film because the gel moved to the loop positions and the cured resin acts as both a vibration damper and an additional mass for vibration of the plate. It should be noted that all the lens heights in the array decreased slightly in the period from 20 to 360 min, as shown in Fig. 4, although the coefficient of linear contraction for the resin was 0.1%. For complete resin curing by UV light, a total energy of approximately 2000 mJ is required, which is estimated to occur at an exposure time of 392 min. Considering the increase of the resistance

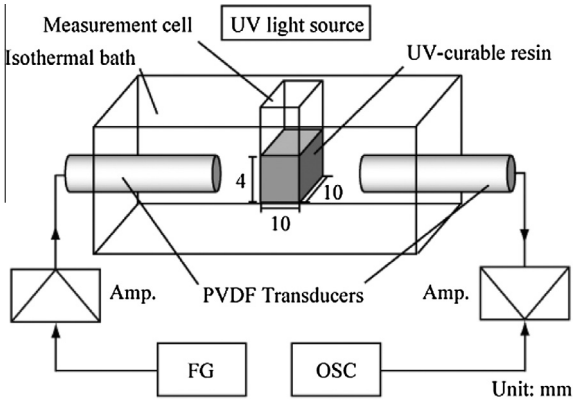

Fig. 9. Setup for the measurement of the sound velocity of the UV-curable resin.

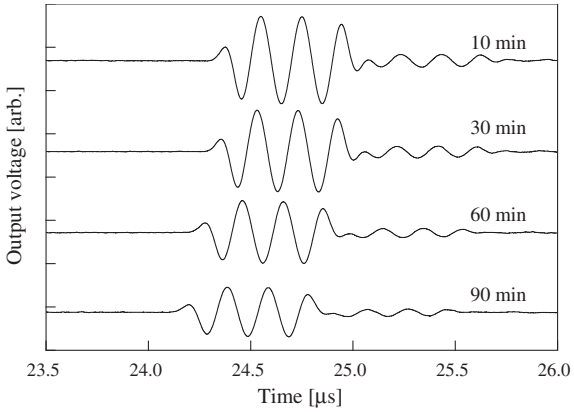

Fig. 10. Waveforms propagating through the gel for several UV exposure times.

shown in Fig. 8, the acoustic radiation force that forms the lens array decreased and the lens height decreased gradually in the period from 20 to 360 min when the input voltage to the transducer was constant.

4. Acoustic characteristics of the UV-curable resin

The acoustic characteristics of the UV-curable resin were investigated. The sound speed of the UV-curable resin under UV exposure was measured by a conventional ultrasonic pulse technique in a water bath, as shown in Fig. 9 [22]. Wide-band polyvinylidene difluoride (PVDF) transducers each with a diameter of 3 mm were used as the ultrasonic transmitter and receiver. A rectangular polystyrene measurement cell (cross-section: 10 × 10 mm^2; wall thickness: 1 mm) with the UV-curable gel was arranged between the two transducers in an isothermal bath. The thickness of gel was controlled to 4 mm while taking the acoustic field radiated from the transducer and the propagation path of the ultrasound wave into consideration. The UV-light source was placed above the measurement cell. For comparison with the experimental results described in the previous section, the temperature of the gel was controlled at 30 °C in the isothermal bath and the gel surface was exposed to UV light with a wavelength of 365 nm at 0.085 mW/cm^2. Strictly speaking, the light intensity of the gel slightly attenuates in the thickness direction of the gel, since the light transmission rate through a 2-mm-thick resin film at a wavelength of 365 nm is 98%. The electric signal of a sinusoidal pulse wave with three cycles and an amplitude of 5 V at the center frequency of 5 MHz was input to the transducer so that the ultrasound pulse wave was transmitted from the transducer and received by the other transducer. Fig. 10 shows representative waveforms propagating through the gel at several UV exposure times. The acoustic characteristics of the gel can be measured by replacing the gel and water in the measurement cell and comparing the two waveforms propagating through the gel and water. The sound speed of the gel was estimated from the time difference of arrival between the two waves. Although the multiple reflections at the wall of the cell occur, this effect can be subtracted by comparing the two waveforms. The arrival time of the pulse wave was determined from the fifth zero-crossing point. Fig. 11 shows the change in the sound speed of the UV-curable resin with respect to UV exposure time. The sound speed of the gel increased from 987 to 1006 m/s (increase of 1.9%) as the UV exposure time increased. The sound speed gradually increased after approximately 10 min and began to saturate at 90 min. It should be noted that the sound speed of the gel did not reach its maximum value perfectly and continued to increase after 360 min, even though the resin was expected to be completely cured at an exposure time of 392 min.

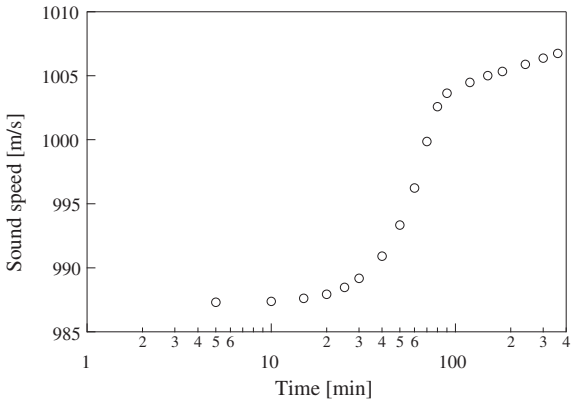

Fig. 11. Change in the sound speed of the UV-curable resin with respect to the UV exposure time.

From the change in sound speed shown in Fig. 11, the attenuation of the ultrasound in the gel can be estimated. By taking into account the acoustic reflection at the boundaries between the water and the measurement cell, and the cell and gel, the attenuation coefficient of the ultrasound propagation in the gel α [dB/cm] can be expressed as

$$\alpha = \frac{20}{l} \log \left\{ \frac{V_w}{V_g} \frac{\rho_g c_g (\rho_w c_w + \rho_p c_p)^2}{\rho_w c_w (\rho_g c_g + \rho_p c_p)^2} \right\}, \quad (1)$$

where l is the length of the gel through the propagation path (10 mm), V_w and V_g are the peak to peak values of the received pulse signal (third positive value to the negative peak) through the water and gel, respectively, ρ_w (=996 kg/m^3), ρ_p (=1050 kg/m^3), and ρ_g are the densities of water, the measurement cell, and the gel, respectively, and c_w (=1509 m/s), c_p (=2340 m/s), and c_g are the sound speeds of water, the measurement cell, and the gel, respectively. Although the coefficient of the linear contraction of the gel was 0.1% and the density of the gel ρ_g changed slightly as the curing time increased, we assumed that ρ_g was constant to calculate the attenuation coefficient. The attenuation in surrounding water and the polystyrene cell can be subtracted by comparing two waveforms in the case that the cell is filled with water and the gel. The attenuation coefficients were measured at several frequencies from 4 to 7 MHz by changing the driving frequency of the transducer. Fig. 12 shows the changes in the ultrasound attenuation of the UV-curable resin with respect to UV exposure time at several frequencies. The attenuation was calculated from (1) by taking the change in sound speed in Fig. 11 into consideration. The attenuation

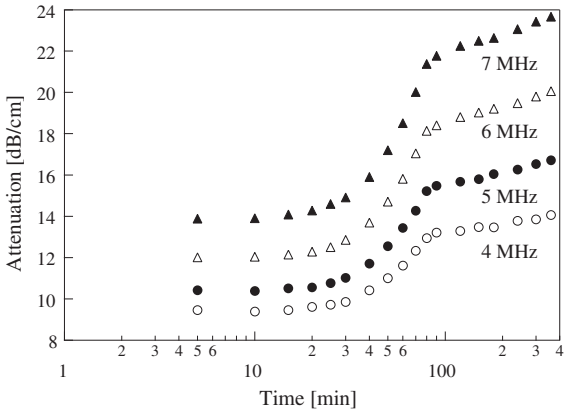

Fig. 12. Change in the ultrasound attenuation of the UV-curable resin with respect to the UV exposure time at several frequencies.

increased gradually after 10 min and began to saturate at 90 min at all the frequencies, which was the same tendency as that of the sound speed in Fig. 11, and the attenuation increased as the frequency increased. Therefore, both the sound speed and attenuation increased as the UV-curable resin cured with an increasing exposure time. This tendency corresponds with the change in the quality factor of the lens array in Fig. 8, although the measurement conditions, such as the thickness of the gel and the ultrasonication, in the two experiments are quite different. In the lens array, a continuous high-intensity ultrasound at a low frequency was used. On the other hand, in this section, a low-intensity-pulsed ultrasound at a high frequency with a pulse repetition frequency of 400 Hz and an amplitude of a few hundred Pa was used. That is to say, the larger ultrasound attenuation of the resin causes the lens array to have a lower quality factor. It seems that the resin curing of the lens array in Fig. 8 was somewhat accelerated compared with the result in Fig. 12. It is possible that the ultrasonication accelerated the resin curing, or the local temperature rise of the gel around the ultrasound transducer affected the curing time even though the temperature of the gel surface was 30 °C.

5. Conclusions

A technique for the formation of an optical lens array was proposed using a UV-curable resin and ultrasonication. The gel film of UV-curable resin was deformed by the acoustic radiation force from the flexural vibration of the glass plate. Irradiation with UV light during deformation of the gel film resulted in fabrication of the lens array. The curing state of the gel was determined based on the electrical admittance of the transducers. The acoustic characteristics of the UV-curable resin were measured by a pulsed ultrasound. The sound speed and the attenuation of the resin increased as the UV exposure time increased. This technique can be applied to the fabrication of a microlens array using driving frequencies above 200 kHz.

Acknowledgments

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